



Geochemistry of core sediments along the Active Channel, northeastern Indian Ocean over the past 50,000 years: Sources and climatic implications

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ABSTRACT

Major and trace elements of sediments from two gravity cores (10YDY09 and 12I712) in the northeastern Indian Ocean have been analyzed for sediment provenance and the relationship of the sediments with climate change since 50 ka. The rare earth element (REE) compositions were analyzed, and the sediment contributions were estimated for the major potential sources, including the Ganges-Brahmaputra (G-B), Godavari-Krishna (G-K) and Mahanadi Rivers. Our results showed that the sediments in the study area were a mixture of sediments discharged from the above three rivers. The sediment contribution of the G-K Rivers increased notably during the Holocene when the rainfall increased, which may be caused by the strengthening of the East Indian Coastal Current (EICC) and the resulting large amounts of sediments supplied by the G-K Rivers. The higher sediment contribution from the G-B Rivers demonstrated the role of the Active Channel in transporting sediments to the distal Bengal Fan. During the last glacial maximum (LGM), especially in the late period, the Indian summer monsoon weakened, but the winter monsoon strengthened, resulting in a decrease in chemical weathering and elemental enrichment in the northeastern Indian Ocean. Conversely, when the rainfall was low, the chemical weathering strengthened and K_2O/TiO_2 ratios were lowered due to the longer weathering time and resulting sediment potassium loss. However, when the sea level reached a certain height during the Holocene, the fluvial sediments could not easily enter deep-water environments through submarine channels, which were well developed in the Bengal Fan.

1. Introduction

Geochemical compositions are widely used to evaluate the sources and climatic variations in marine sediments (Kurian et al., 2008; Wei et al., 2004; Yang et al., 2003) because the elemental compositions of marine sediments are mainly controlled by the source rocks (Pereira et al., 2018), weathering processes (Wei et al., 2003), and human activities (Orani et al., 2018; Rao et al., 2015; Worakhunpiset, 2018). Among these geochemical compositions, trace elements such as Th, Zr, Hf, Nb, Sc, Cr, Ni, V, Ba, Rb and rare earth elements (REEs) are refractory with low mobility during weathering and transportation processes, and thus these elements can generally be utilized for sediment provenance determination (Bayon et al., 2015; Dou et al., 2015; Wei et al., 2012). For the major elements, the normalized weathering indices (such as K/Si and K/Ti) can be applied to reconstruct the temporal variations in the chemical weathering (Gruetzner and Higgins, 2010;

Lupker et al., 2013).

The Bengal Fan in the northeastern Indian Ocean is the largest submarine fan in the world (Weber et al., 1997). This fan is surrounded by the Indian Peninsula to the west, Bangladesh and the Himalayas to the north, and the Andaman Sea and Southeast Asia to the east (Li et al., 2017). The main major rivers that discharge sediments into the Bengal Fan include the Ganges, Brahmaputra, Mahanadi, Krishna, Godavari and Irrawaddy Rivers. While sediments from several large rivers in eastern India enter the western side of the Bay of Bengal (BoB), the massive sediment supply through the Ganges and Brahmaputra Rivers plays a key role in the BoB (Curry et al., 2002). Studies over the past decade revealed that large amounts of erosional products from the Himalayas were shed into downstream depocenters due to the collision between India and Asia, resulting in the uplift of the Tibetan Plateau (Curry, 1994; Einsele et al., 1996).

The Bengal Fan is marked by a series of channels or fan valleys, and

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the main central channel (also known as the Active Channel or Swatch of No Ground) that is directly connected to the submarine canyon is important for the extension of the channel length outside the BoB (Curry et al., 2002). During high sea level conditions, such as the present, the canyon does not directly receive sediments from the large rivers, and turbidity currents decrease and occur less frequently (Curry et al., 2002; Galy et al., 1996).

The monsoonal winds generate large seasonal variations in the ocean currents. In the northeastern Indian Ocean, the surface currents reverse when the wind direction changes seasonally; that is, the surface currents shift from a cyclonic gyre during the winter monsoon to an anticyclonic gyre during the summer monsoon (Hacker et al., 1998; Schott and McCreary, 2001; Vinayachandran et al., 1999). The East Indian Coastal Current (EICC, also known as the West Bengal Boundary Current) flows northward during the southwest monsoon in the summer, whereas the EICC turns southward in the winter (Sarma et al., 2018; Shankar et al., 2002).

Previous work in the BoB mainly focused on the upper and middle parts of the Bengal Fan and the eastern continental margin of India (Li et al., 2017; Mazumdar et al., 2015; Tripathy et al., 2014). Modern studies indicated that sediments in the Bengal Fan were mainly sourced from terrigenous materials transported by rivers including the erosional products of the Himalayas, Indian Peninsula and Indo-Burman Ranges (Li et al., 2017; Phillips et al., 2014; Tripathy et al., 2014). Based on geochemical analyses, (Tripathy et al., 2014) further estimated the sediment contribution of the Himalayas and Indian Peninsula materials to the western Bengal Fan. However, previous publications have seldom referred to sediment sources along the channels in the northeastern Indian Ocean.

In this paper, we analyze geochemical proxies to identify the probable sediment sources of two cores around the Active Channel. Here, Geochemical indices are also applied to interpret the paleoenvironmental changes in the BoB by comparing the similarities and differences of the geochemical element behaviors within the glacial/interglacial cycles, which may aid in better understanding climate changes since 50 ka. Additionally, we explore the influence of sediment supply from the Ganges-Brahmaputra (G-B) Rivers by comparing the sediment sources of two cores obtained in the study area.

2. Materials and methods

Two gravity cores, 10YDY09 (9°59.61'N, 85°57.66'E, water depth of 3520 m) and 12I712 (4°0.33'N, 82°30.20'E, water depth of 4181 m), were drilled in the northeastern Indian Ocean (Fig. 1) and have lengths of 240 cm and 295 cm, respectively. The measured samples were gathered at 4-cm intervals in cores 10YDY09 and 12I712. After being dried off at 60 °C, the organic matter and carbonate were removed from the bulk sediment samples with hydrogen peroxide (10%) and acetic acid (10%), and then the samples were centrifuged five times with deionized water until the centrifugal liquid remained stable (pH = 7.5). Major and trace elements except SiO₂ were measured using inductively coupled plasma atomic emission spectrometry (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. The analytical results indicated that the differences for major and trace elements are less than 10% and most are less than 5%.

The preliminary age model was reconstructed based on the AMS ¹⁴C dating of mixed planktonic foraminifera in the core sediments (Table 1) by linear interpolation within the dating layers and extrapolation outside the dating layers. All ¹⁴C ages were converted to “calendar ages” using the CALIB Program (Reimer et al., 2013) after a global 400-year reservoir age correction was applied. Because we focus on the sediment provenance and climate influence since 50 ka, in this study, we discuss only the upper 179 cm of core 10YDY09 and upper 250 cm of core 12I712. The time resolution of cores 10YDY09 and 12I712 is 900–1100 years.

We use a chemical index as a proxy for evaluating the variation

pattern of the chemical weathering intensity. The chemical index (chemical index of alteration, CIA) is calculated as follows: $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where the oxide abundances are in molar units and CaO* is the silicate-derived CaO concentration in the sediments (Nesbitt and Young, 1982).

3. Results

3.1. Major elements

Major elements are generally utilized to trace weathering process in depositional environments. In the drainages around the BoB, the Ti and Fe concentrations in the Godavari-Krishna and Mahanadi River sediments are higher than those in the sediments of the Ganga-Brahmaputra and Irrawaddy Rivers, while the Al contents in the Irrawaddy and Mahanadi River sediments are higher than those of the G-B and G-K Rivers (Table 2).

We divided core 10YDY09 into six stages by comprehensively considering the variation patterns of the TiO₂, Al₂O₃, K₂O, Na₂O and P₂O₅ concentrations (Fig. 2). The concentrations of most major elements remained stable during Stage 1 (50–28 ka), except for the MnO concentration, which shows a constant descending trend during this stage. During Stage 2 (28–23 ka), the concentrations of TiO₂, Al₂O₃ and K₂O increased gradually until reaching peaks at 23–24 ka, while the concentrations of MgO, Fe₂O₃ and MnO decreased. The concentrations of TiO₂, Al₂O₃, K₂O and Fe₂O₃ remained high during Stage 3 (23–19 ka). At approximately 19 ka, the concentrations of TiO₂, Al₂O₃ and K₂O decreased abruptly. During Stage 4 (19–15 ka), the concentrations of TiO₂ and Al₂O₃ increased continuously, while those of MgO and CaO decreased gradually. During Stage 5 (15–9 ka), the concentrations of TiO₂, Al₂O₃, K₂O and MgO remained higher, while the CaO concentration was relatively low during this stage. During the past 9 ka (Stage 6), the TiO₂, Al₂O₃, K₂O, Na₂O and MgO concentrations decreased constantly, while the CaO concentration increased.

In core 12I712, we also divided the variations in the major element concentrations into six stages according to the concentration variation patterns of some major elements (TiO₂, Al₂O₃ and P₂O₅). During Stage 1 (50–45 ka), the concentrations of TiO₂, Al₂O₃, CaO and P₂O₅ changed with great amplitude, while the MnO concentration remained low during this stage. During Stage 2 (45–42 ka), the concentrations of Na₂O and P₂O₅ were obviously lower than during the previous stage, while the CaO, MgO, Fe₂O₃ and MnO concentrations reached peaks at approximately 43 ka. During Stage 3 (42–28.5 ka), the concentrations of Na₂O, K₂O and P₂O₅ were higher than during the previous stage, while the MnO concentration remained low, which is similar to Stage 1. During the following two stages (Stage 4, 28.5–22 ka and Stage 5, 22–15 ka), the concentrations of TiO₂, Al₂O₃, K₂O and P₂O₅ remained low, while the CaO and MnO concentrations were higher than during the previous stage. At approximately 22 ka, the concentrations of K₂O and Na₂O increased abruptly, while the MgO and MnO concentrations decreased. During the last stage (Stage 6, since 15 ka), the concentrations of TiO₂ and Al₂O₃ have clearly increased, but the concentrations of K₂O, Na₂O and P₂O₅ have remained low.

3.2. Rare earth elements (REE)

The REEs were analyzed in the samples to evaluate the possible change in source materials. In core 10YDY09, the ΣREE concentration ranges from 113.6 μg/g to 187.5 μg/g, with an average value of 147.8 μg/g. Similarly, in core 12I712, the ΣREE concentration ranges between 121.0 μg/g and 202.8 μg/g with an average of 164.5 μg/g. Both concentrations are higher than those of the G-B Rivers but lower than those of the Godavari-Krishna (G-K), Mahanadi, and Irrawaddy Rivers (Table 3).

The distribution patterns of the upper continental crust (UCC) normalized REE concentrations in cores 10YDY09 and 12I712 were

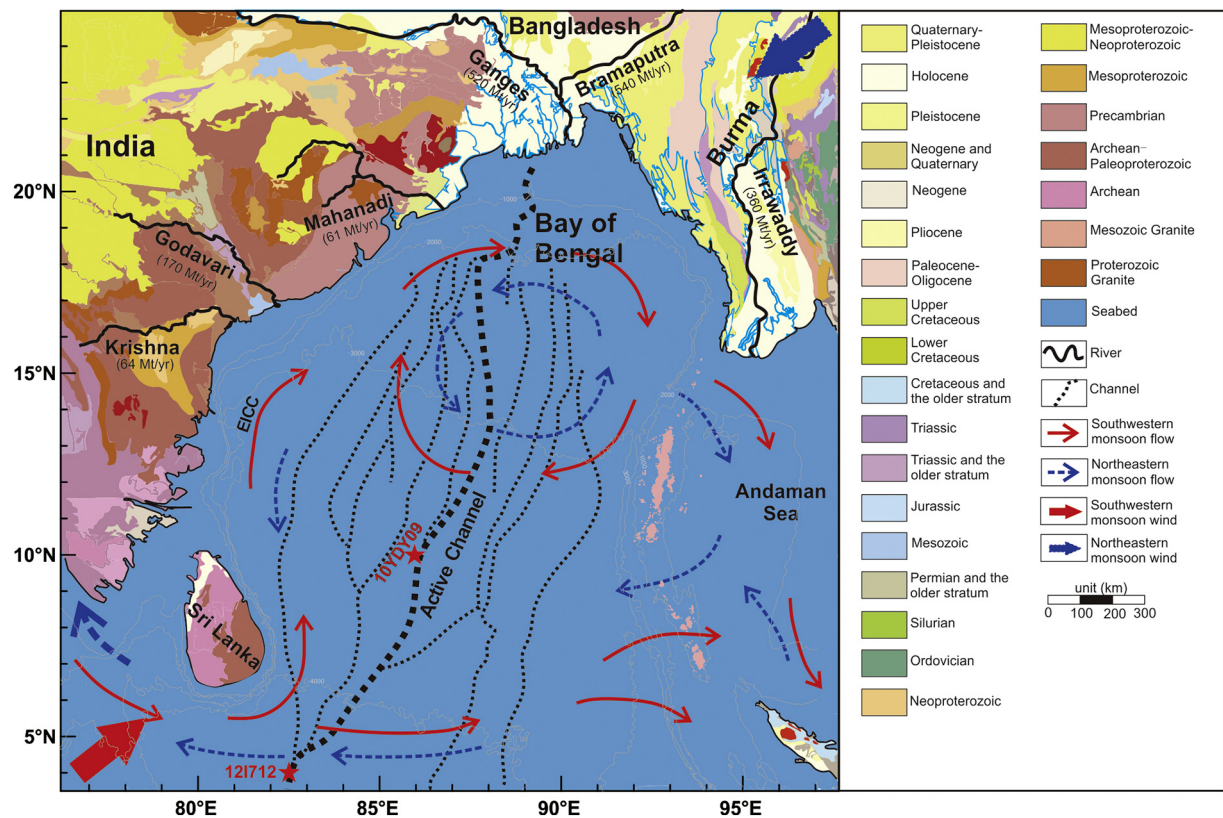


Fig. 1. Locations of gravity cores 10YDY09 and 12I712, Indian monsoon and current circulation (Schott and McCreary, 2001) in the northeastern Indian Ocean. The major potential sources of sediments to this location are the rivers draining the Himalayas (Ganges and Brahmaputra Rivers), Indian-Peninsula (Godavari, Krishna and Mahanadi Rivers), and Indo-Burman Range (Irrawaddy River). The sediment loading data of these rivers are from (Milliman and Farnsworth, 2011). The geological background is adapted from the International Geological Map of Asia (Ren, 2013).

distinguished from those of the Irrawaddy River and Gede Volcanic Complex (GVC, Fig. 3). The patterns seem to be mixtures of northern Himalayan materials discharged by the G-B River system as well as western Indian Peninsula materials transported by the G-K River system and Mahanadi River. Therefore, we select the G-B, G-K and Mahanadi Rivers as the key end-members in the subsequent analysis of the sediment provenance.

3.3. Principal component analyses

To identify the major factors responsible for the major and trace elemental changes in the sediment samples, principal component analyses of the elements were performed using SPSS Statistics 19.0

software. There are five components with eigen values greater than 1, which could explain more than 85% of the total variance in the dataset from core 10YDY09 and more than 75% for core 12I712 (Table 4). To directly show the variation features of the major elements in the core sediments, we chose one characteristic element from each principal component.

In core 10YDY09, the dominant principal component (PC1) is loaded with lithogenic elements (e.g., K_2O , Al_2O_3 , TiO_2 and Na_2O) as well as several high field strength elements (e.g., Th, U, Nb, Ta, and REEs) and large ion lithophile elements (e.g., Rb, Cs, and Ba), representing terrigenous material contributions. PC1 also has typical biophile elements (Ba, Sr, Cu, Ni and Zn) with higher negative loadings. Among the elements in this component, the Rb concentration remained

Table 1
AMS ^{14}C and calibrated calendar ages in cores YDY09 and 12I712 in the northeastern Indian Ocean.

Lab-ID	Depth (cm)	Materials	$\delta^{13}C$ (‰)	^{14}C ages (a)	Calendar ages (a)
391114	YDY09 3–4 cm	Mixed planktonic foraminifera	1.4	2100 ± 30	1669 ± 52
391115	YDY09 19–20 cm	Mixed planktonic foraminifera	0.8	7260 ± 30	7716 ± 42
391116	YDY09 30–32 cm	Mixed planktonic foraminifera	0.6	9490 ± 30	10,323 ± 59
391117	YDY09 62–63 cm	Mixed planktonic foraminifera	0.7	13,480 ± 40	15,688 ± 98
408431	YDY09 124–125 cm	Mixed planktonic foraminifera	1.3	23,290 ± 80	27,255 ± 105
408432	YDY09 168–169 cm	Mixed planktonic foraminifera	0.9	42,790 ± 600	45,651 ± 534
408433	12I712 21–22 cm	Mixed planktonic foraminifera	1.3	5780 ± 30	6215 ± 36
408434	12I712 36–37 cm	Mixed planktonic foraminifera	0.8	10,310 ± 30	11,281 ± 56
408435	12I712 77–78 cm	Mixed planktonic foraminifera	1.1	23,640 ± 90	27,500 ± 94
408436	12I712 147–148 cm	Mixed planktonic foraminifera	0.7	31,160 ± 160	34,689 ± 164
408437	12I712 199–200 cm	Mixed planktonic foraminifera	1.3	38,680 ± 370	42,397 ± 251

All raw radiocarbon dates were converted to 2σ calendar ages with CALIB 7.1.0 software using MARINE13. A ^{14}C calibration dataset (Reimer et al., 2013) was used without any further adjustment for the regional ^{14}C reservoir age (ΔR , deviation from the average global reservoir age of approximately 400 years). Numbers after ± are the corresponding errors (2σ errors) for the ages.

Table 2

Major element concentrations in the sediments of cores 12I712 and 10YDY09 in the northeastern Indian Ocean compared with possible source areas.

Sample		Al ₂ O ₃ (%)	CaO (%)	Fe ₂ O ₃ (%)	K ₂ O (%)	MgO (%)	MnO (%)	Na ₂ O (%)	P ₂ O ₅ (%)	TiO ₂ (%)
12I712	Aver.	17.81	0.93	9.34	2.96	2.92	0.08	0.78	0.30	0.82
	Stdev	1.55	0.17	1.43	0.68	0.32	0.04	0.31	0.18	0.08
	Min.	14.33	0.45	5.75	1.85	2.21	0.05	0.26	0.12	0.64
	Max.	20.52	1.60	17.06	4.6	4.55	0.28	1.60	0.82	1.00
10YDY09	Aver.	16.63	0.88	8.34	2.92	2.95	0.09	0.77	0.30	0.72
	Stdev	2.24	0.21	0.99	0.83	0.24	0.03	0.36	0.12	0.09
	Min.	13.62	0.35	5.62	1.58	2.24	0.05	0.37	0.11	0.59
	Max.	20.48	1.60	10.95	4.37	3.29	0.15	2.09	0.62	0.89
Ganges River ^a	Aver.	7.90	2.10	4.60	2.30	1.50	0.09	0.70	–	0.50
Brahmaputra River ^a	Aver.	8.00	1.40	4.10	2.60	1.60	0.10	1.30	–	0.40
Godavari-Krishna Rivers ^b	Aver.	8.04	2.03	6.35	1.67	1.50	0.08	–	–	0.82
Mahanadi River ^c	Aver.	18.8	0.27	7.8	3.0	1.9	0.02	0.50	0.09	0.93
Irrawaddy River ^d	Aver.	11.89	1.51	4.40	1.87	1.50	0.08	1.37	0.08	0.69
GVC ^e	Aver.	18.80	8.10	8.07	1.30	3.30	0.20	3.10	0.20	0.80

–: no data.

All elemental data refer to core top sediment samples or surface sediment samples in the cited references.

^a (Tripathy et al., 2014).^b (Pattan et al., 2008).^c (Mazumdar et al., 2015).^d (Hossain et al., 2017).^e (Handley et al., 2009).

low during Stages 1 and 4, reaching peaks during Stages 3 and 5, but showed the opposite trends during Stages 2 and 6 (Fig. 4). PC2 has positive loadings of Cr and Fe₂O₃ but negative loadings of CaO and may represent the stable provision of the terrestrial fraction, which is mainly supplied from the proximal source area. The Cr concentration remained stable during Stages 1, 3 and 6 but changed to a certain extent during the other stages, with an increasing trend during Stage 4 and decreasing trend during Stage 5. PC3 was thought to be authigenic deposition with a characteristic element of Tl, which shows a higher value during Stage 3. The Tl concentration during Stage 4 was obviously lower during Stages 3 and 5, with decreasing trends during Stages 1 and 6. PC4 mainly consists of Hf and Zr, which are the significant components of zircon, showing high negative loading. We can suggest that this principal component is the terrigenous supply from a distant source area. The Hf concentration was low during Stages 1, 3 and 5 but showed increasing trends during Stages 2 and 4. PC5 may represent the terrigenous components transported by ocean currents due to the indications of Mo and As being in a redox environment (Stummeyer et al., 2002). The Mo concentration remains low during Stage 3, with an increasing trend during Stages 5 and 6, but the concentration was relatively high during Stage 1.

In core 12I712, the dominant principal component (PC1) explains approximately 52.5% of the total variance (Table 4) and is loaded primarily with positive loadings of lithogenic elements (U, Th, Bi, Y, Pb, and Na), probably indicating the combined influence of Himalayan materials and Indian terrestrial components. The U concentration decreased gradually during Stages 1 and 2, and a slight decreasing trend was seen during Stages 4 and 5 (Fig. 4). PC2 with positive loadings of Al₂O₃ and K₂O also mainly comes from terrigenous components of the northern source area. Past studies already showed the enrichment of Al in sediments of the Irrawaddy River and high K concentrations in the sediments of the G-B River drainages (Garzanti et al., 2011; Hossain et al., 2017; Pattan et al., 2008). The Li concentration remained high during Stage 6 and low during Stages 4 and 5 and showed greatly changing amplitudes during Stages 1, 2 and 3. PC3 had positive loadings of Fe₂O₃, MgO and MnO and was considered to be a terrestrial component from the Indian Peninsula transported by the G-K Rivers. Compared with those discharged from the G-B River system, the sediments from the Indian Peninsula are rich in Fe, V and Cu (Alagarsamy and Zhang, 2010; Roonwal et al., 1997). The V concentration remained low during Stage 5 and relatively low during Stages 1, 3 and 6 and showed a greatly changing amplitude during Stage 4. PC4 had positive

loadings of Cd, Tl and In and negative loadings of Ti and Mo, which might be related to volcanic activity (McCave and Carter, 1997; Wei et al., 2012). The Cd concentration remained low during the first three stages, but a more clearly changing amplitude was seen during the last three stages. From 32 ka to 29 ka, the Cd concentration increased constantly from ~0.3 ppm to ~0.7 ppm. PC5 had positive loadings of Sr, CaO and Zr but negative loadings of Cr, which may be controlled by a mixture of terrigenous and authigenic deposits (Fralick and Kronberg, 1997; Pattan et al., 2013; Schnetger et al., 2000; Sun et al., 2008). The Sr concentration remained low during Stages 3 and 6 but was high during Stages 4 and 5.

4. Discussion

4.1. Sediment provenance

Many factors are responsible for the compositional deviation of detrital sediments from parent rocks, such as chemical weathering, dynamic sorting during transport, post depositional diagenesis and anthropogenic activity (Joussain et al., 2017; Robinson and Johnsson, 1997; Yang et al., 2008). Previous studies revealed that elements including the REE, Sc, Ti, Co, Zr, Hf, Th and Nb could be used for the provenance discrimination of river and marine sediments because these elements mostly reside in mineral lattices, behave conservatively in hypergene environments and are resistant to chemical weathering (He et al., 2015; Picouet et al., 2002; Yang et al., 2003). The compatibility of elements in magmatic differentiation showed that Sc, Ti, Cr and Co were first precipitated in magmatic differentiation, and usually concentrated in mafic minerals, whereas La, Zr, Nb, Th, Hf and Ta were precipitated in the late stage of magmatic differentiation and enriched in felsic minerals; hence, the content characteristics of La and Th could reflect the lithologic composition of the source region to some extent (Das et al., 2006; Yang et al., 2008). Therefore, we select Th–La to identify the potential sediment sources of cores 10YDY09 and 12I712.

In the northeastern Indian Ocean, the concentrations of Th and La in the sediments of cores 10YDY09 and 12I712 were located between the corresponding compositions of three end-members, the G-B, G-K and Mahanadi Rivers (Fig. 5), indicating that the two core sediments in the study area were probably mixtures of the above three sources. Due to the lack of sediment loadings from Sri Lanka and nearly complete overlap between Sri Lanka and the Mahanadi River, we can only estimate the contribution of the Mahanadi River sediments which also

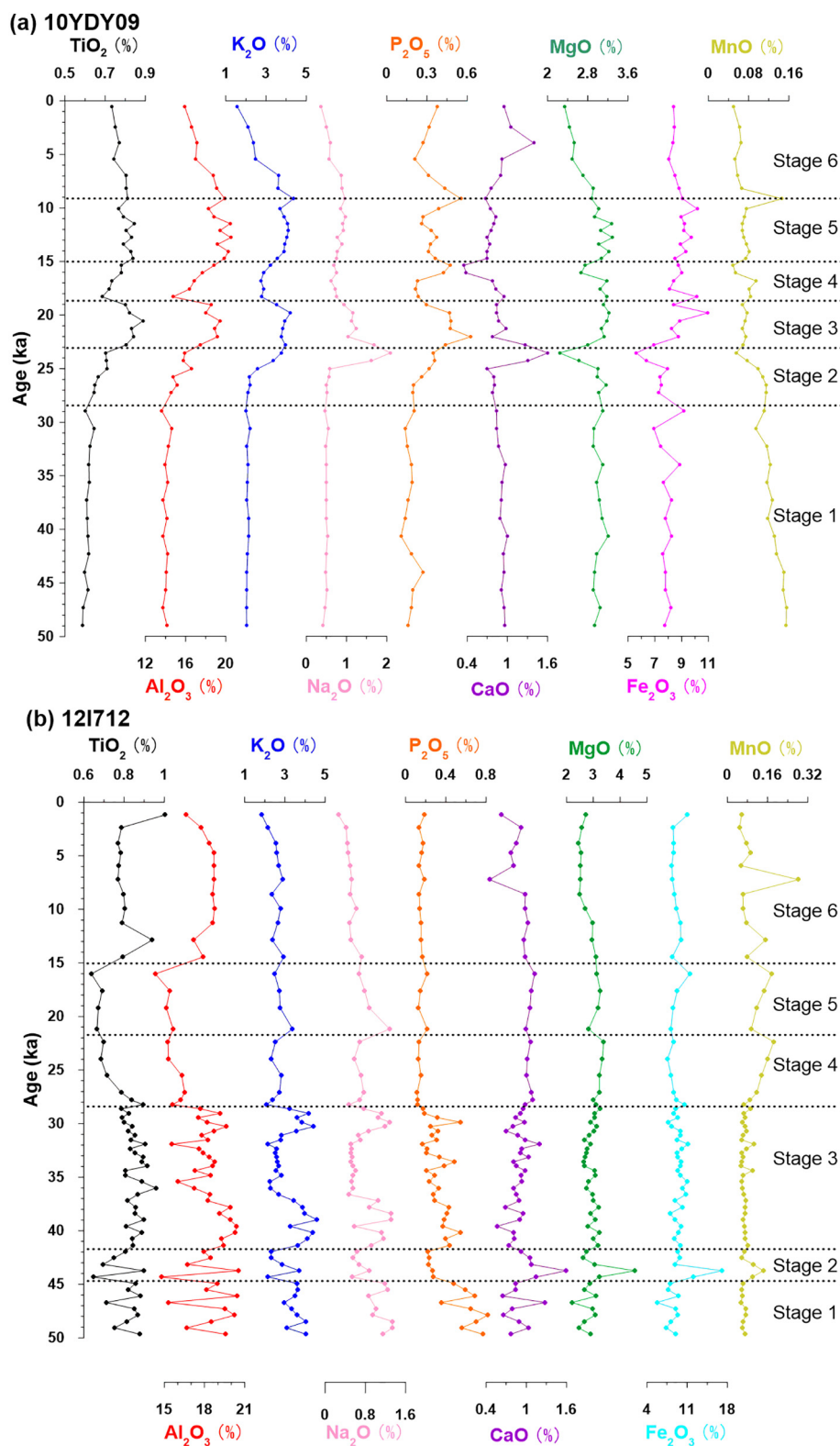


Fig. 2. Variation patterns of major elements, Al₂O₃, K₂O, CaO, Fe₂O₃, Na₂O, MgO, MnO, P₂O₅ and TiO₂, in the sediments of cores 10YDY09 (a) and 12I712 (b). The horizontal dashed lines mark the boundaries of the divided stages.

contain the sediment contribution of Sri Lanka here. Meanwhile, most sediments from the Irrawaddy River are generally transported eastward into the Andaman Sea, and the sediments in the central BoB are predominantly derived from the Himalayas, and other sources including the Indian Peninsula and Myanmar were usually ignored (Galy et al., 2008; Goodbred, 2003), especially during the Holocene (Li et al.,

2018). The REE patterns shown in Fig. 4 confirm the sediment contributions from the G-B, G-K and Mahanadi Rivers.

Efforts were made to quantify the contribution of the major provenances to the sediments in cores 10YDY09 and 12I712 using the minimum error methods of (Liu et al., 2012; Liu et al., 2013) between the real and estimated values. First, various sediment sources and their

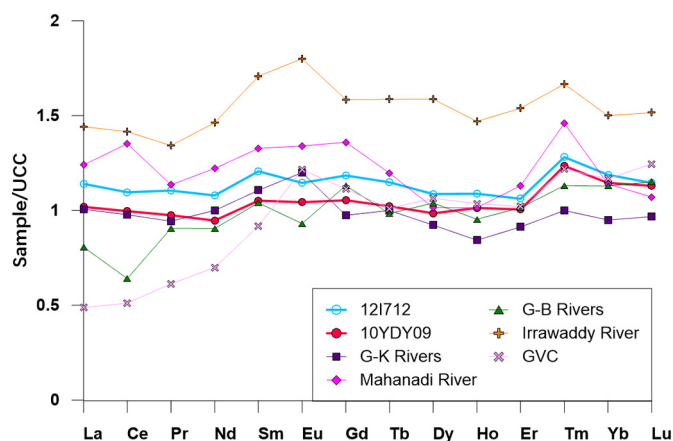
Table 3

REE parameters in the sediments of cores 12I712 and 10YDY09 in the northeastern Indian Ocean, compared with those of the proximal rivers sediments and UCC.

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE
10YDY09	31.2 (4.9)	61.8 (10.0)	6.8 (1.2)	25.2 (4.5)	4.8 (0.8)	1.02 (0.10)	4.11 (0.67)	0.70 (0.11)	3.76 (0.53)	0.82 (0.11)	2.27 (0.27)	0.36 (0.04)	2.26 (0.24)	0.35 (0.03)	145.6 23.1
12I712	35.4 (4.3)	68.9 (9.0)	7.8 (1.0)	29.1 (4.0)	5.6 (0.8)	1.14 (0.12)	4.72 (0.65)	0.80 (0.11)	4.21 (0.56)	0.90 (0.12)	2.43 (0.31)	0.38 (0.05)	2.37 (0.30)	0.35 (0.05)	164.1 (20.9)
Ganges-Brahmaputra Rivers ^a	25.0	40.4	6.4	24.4	4.9	0.93	4.52	0.69	4.05	0.79	2.33	0.34	2.26	0.36	117.5
Godavari-Krishna Rivers ^b	31.2	61.6	6.70	27.0	5.20	1.20	3.90	0.70	3.60	0.70	2.10	0.30	1.90	0.30	146.4
Mahanadi River ^b	38.5	85.2	8.1	33.0	6.2	1.34	5.44	0.84	3.96	0.84	2.60	0.44	2.28	0.33	189.0
Irrawaddy River ^c	44.7	89.2	9.5	39.5	8.0	1.80	6.34	1.11	6.19	1.22	3.54	0.50	3.00	0.47	215.1
GVC ^d	15.1	32.2	4.4	18.9	4.3	1.22	4.45	0.71	4.15	0.86	2.35	0.37	2.33	0.39	91.7
UCC ^e	31.0	63.0	7.1	27.0	4.7	1.00	4.00	0.70	3.90	0.83	2.30	0.30	2.00	0.31	148.1

Numbers in brackets denote the standard deviations of the rare earth elements.

All elemental data refer to core top sediment samples or surface sediment samples in the cited references.

^a (Stummeyer et al., 2002).^b (Mazumdar et al., 2015).^c (Kurian et al., 2008).^d (Handley et al., 2009).^e (Rudnick and Gao, 2014).**Fig. 3.** Normalized patterns in the sediments of cores 10YDY09 and 12I712 in the northeastern Indian Ocean and possible sources. The REE concentrations are normalized by the UCC (Rudnick and Gao, 2014). REE data of possible sediment sources contain those of the G-K Rivers (Mazumdar et al., 2015), Mahanadi River (Mazumdar et al., 2015), G-B Rivers (Stummeyer et al., 2002), Irrawaddy River (Kurian et al., 2008) and GVC (Handley et al., 2009).

compositions are assigned in the study areas. Second, the preliminary coefficients of each source are designated. Third, the estimated values are acquired together with the corresponding real values. Finally, the coefficients are continuously adjusted until the error between the estimated and real values reaches a minimum. In this work, the potential end-members contain the G-B, G-K and Mahanadi Rivers. This calculation is based on the Th and La concentrations, which can be discriminated from various potential sources (Fig. 5). In the study area, the sediment contribution of the G-B Rivers in core 10YDY09 were higher than those in core 12I712, while core 10YDY09 showed less Mahanadi River-sourced sediment deposits. Under the influence of the EICC, the G-K River-originated sediments account for 40–50%. Before the LGM, the Mahanadi River hardly supplied sediments to core 10YDY09, while the G-K Rivers supplied approximately 50–60% of the sediments to this core (Fig. 6), indicating that the channels widely developed in the BoB were a notable path for the northern terrigenous sediments entering the sea during the low sea level when the turbidity deposition developed, resulting in near-source deposition in this core. With the gradual ascent of the sea level since the LGM, the contribution of the G-B River sediments decreased, and the sediments from the G-K Rivers increased under the influence of the EICC. However, during the LGM at core 12I712 outside of the BoB, the sediment contribution of the G-B Rivers

reached its peak but was nearly undistinguishable from the sediment contribution of the Mahanadi River, indicating that large amounts of the G-B River sediments were transported and further deposited in the front of the Bengal Fan, which likely occurred by means of the channels (especially the Active Channel) developed on the Bengal Fan.

4.2. Chemical weathering

Information on the different geochemical compositions of sediments from various sources are recorded in the BoB sediments. The authigenic Ti is negligible and generally thought to be terrestrial, barely changing during the transport process of sediments. Thus, Ti is normally considered to be the best proxy for terrestrial materials in marine sediments (Wei et al., 2003; Young and Nesbitt, 1998). Feldspar and mica weathering to smectite and kaolinite results in potassium loss in the weathering profiles (Colin et al., 2006; Nesbitt and Young, 1982), whereas Ti is resistant and can be enriched in the weathering products. The Ti-normalized ratios are normally utilized to eliminate the effects of grain size on the element concentrations. To retrieve information about variation pattern of the chemical weathering intensity of the source area in the study area, the elemental ratio of K_2O/TiO_2 as well as the chemical weathering index CIA are applied.

In core 12I712 outside the BoB, K_2O/TiO_2 and CIA changed from 1.84 to 5.25 with an average of 3.72 and from 72.4 to 85.9 with an average of 79.2, respectively. Before the Holocene, chemical weathering strengthened under the warm climate conditions when the rainfall increased, and the detrital material transported from the source area experienced K loss on land and resulted in high K_2O/TiO_2 ratios in marine sediments. Conversely, cold climate conditions with less rainfall resulted in weakened chemical weathering and lower CIA values (Fig. 6). However, the chemical weathering indicated by both the CIA and K_2O/TiO_2 ratios showed less of a relationship with the rainfall during the Holocene, when the global sea level ascended continuously from ~120 m below the present level during the last glacial maximum (LGM, 26.5–19 ka, (Clark et al., 2009)) to only 10–20 m below the present height just before the Holocene (Lambeck and Chappell, 2001; Rohling et al., 2004). This relationship suggested that the sediments discharged from the large rivers to the north could not easily enter the study area through the channels when the sea level ascended continuously until the near present height.

Conversely, in core 10YDY09 in the middle BoB, K_2O/TiO_2 varied between 2.15 and 5.38 with an average of 3.99, while CIA changed from 68.2 to 84.6 with an average of 78.7. At the beginning of the LGM, the weathering indexes (K_2O/TiO_2 and CIA) changed from relatively stable values before the LGM to staged changes since the LGM (Fig. 6).

Table 4

Factor analysis of elements in the sediments of cores 10YDYD09 and 12I712 in the northeastern Indian Ocean.

10YDY09	PC1	PC2	PC3	PC4	PC5	12I712	PC1	PC2	PC3	PC4	PC5
Rb (mg/kg)	0.98	0.00	−0.04	0.12	−0.10	U (mg/kg)	0.93	0.05	−0.11	0.08	0.02
Be (mg/kg)	0.97	−0.04	0.03	0.09	−0.11	Ta (mg/kg)	0.90	0.19	−0.16	0.07	−0.10
Th (mg/kg)	0.97	0.09	0.04	0.11	0.08	Th (mg/kg)	0.84	0.26	−0.22	−0.05	−0.12
Nb (mg/kg)	0.97	−0.09	0.00	0.11	−0.10	W (mg/kg)	0.83	0.24	0.00	0.17	0.20
K ₂ O (%)	0.95	−0.03	−0.03	0.08	−0.25	Bi (mg/kg)	0.82	0.34	−0.21	0.06	0.02
Cs (mg/kg)	0.94	0.19	0.00	0.22	−0.04	As (mg/kg)	0.67	0.17	0.07	−0.33	0.11
TiO ₂ (%)	0.94	0.10	−0.19	0.01	0.13	Y (mg/kg)	0.61	0.56	−0.22	−0.15	0.22
Al ₂ O ₃ (%)	0.94	0.23	−0.14	−0.03	0.11	Pb (mg/kg)	0.59	0.17	−0.16	−0.17	0.06
Ta (mg/kg)	0.94	−0.14	−0.04	0.11	−0.15	P ₂ O ₅ (%)	0.56	0.50	−0.19	−0.32	0.02
In (μg/kg)	0.93	0.21	0.04	0.15	−0.05	Na ₂ O (%)	0.51	0.50	−0.37	0.14	0.51
Ba (mg/kg)	− 0.92	0.02	0.30	0.04	0.17	Al ₂ O ₃ (%)	0.11	0.82	0.02	−0.24	−0.39
ΣREE	− 0.92	0.01	0.31	0.03	0.17	Li (mg/kg)	0.20	0.81	0.21	0.06	−0.31
Bi (mg/kg)	0.89	0.05	0.00	0.36	0.18	K ₂ O (%)	0.40	0.81	−0.15	0.19	0.11
Ga (mg/kg)	0.88	0.36	0.09	0.07	0.21	Ga (mg/kg)	0.18	0.79	0.28	−0.15	−0.38
Y (mg/kg)	0.82	−0.23	0.11	−0.28	−0.19	Cs (mg/kg)	0.55	0.77	−0.06	0.18	−0.03
Cu (mg/kg)	− 0.81	0.27	0.23	0.10	0.25	Rb (mg/kg)	0.55	0.76	−0.18	0.16	−0.02
Ni (mg/kg)	− 0.81	0.36	0.39	−0.07	−0.17	Nb (mg/kg)	0.57	0.76	−0.11	−0.01	0.01
P ₂ O ₅ (%)	0.81	−0.09	−0.16	−0.02	0.05	Be (mg/kg)	0.57	0.76	−0.09	0.18	0.12
Li (mg/kg)	0.74	0.63	0.02	−0.07	−0.02	ΣREE	0.47	0.60	−0.30	−0.42	−0.10
Sr (mg/kg)	− 0.74	−0.47	0.39	−0.08	−0.06	Hf (mg/kg)	0.24	− 0.51	0.01	−0.08	−0.16
MnO (%)	− 0.74	0.16	0.52	0.09	−0.23	V (mg/kg)	0.00	0.08	0.88	0.10	0.12
Zn (mg/kg)	− 0.74	0.31	0.54	0.03	−0.12	Ge (mg/kg)	−0.16	0.10	0.87	−0.11	−0.18
U (mg/kg)	0.71	0.04	0.52	−0.18	−0.26	B (mg/kg)	0.09	0.03	0.87	0.05	0.32
Cd (mg/kg)	0.68	−0.05	0.52	0.20	0.01	Fe ₂ O ₃ (%)	−0.16	0.04	0.83	−0.25	−0.12
Pb (mg/kg)	0.68	−0.08	−0.02	0.27	0.37	MgO (%)	0.03	0.27	0.78	0.39	0.17
Na ₂ O (%)	0.67	−0.63	−0.01	−0.09	−0.37	Co (mg/kg)	−0.30	−0.41	0.76	0.09	−0.05
Cr (mg/kg)	−0.09	0.91	0.06	−0.22	0.23	Zn (mg/kg)	−0.23	−0.18	0.76	0.44	0.23
CaO (%)	−0.12	− 0.85	0.29	0.03	0.06	Sc (mg/kg)	−0.34	−0.10	0.64	−0.34	−0.47
B (mg/kg)	−0.33	0.78	0.16	0.07	−0.37	Cu (mg/kg)	−0.40	−0.55	0.57	0.23	−0.11
Sc (mg/kg)	−0.50	0.72	0.28	−0.08	0.25	Ba (mg/kg)	−0.15	−0.21	0.51	0.47	0.40
Ge (mg/kg)	0.43	0.70	−0.01	0.27	0.09	MnO (%)	−0.12	−0.34	0.47	0.45	0.30
Fe ₂ O ₃ (%)	0.38	0.62	−0.14	0.54	0.09	Ni (mg/kg)	−0.23	−0.19	0.37	0.10	0.09
MgO (%)	0.04	0.61	0.24	0.40	−0.46	Cd (mg/kg)	0.08	0.07	0.05	0.74	0.02
Co (mg/kg)	−0.53	0.57	0.46	0.00	−0.13	TiO ₂ (%)	0.01	0.28	0.14	− 0.63	−0.37
W (mg/kg)	0.10	0.42	0.18	0.02	−0.10	In (μg/kg)	0.29	0.50	0.10	0.59	−0.15
Tl (mg/kg)	0.05	0.03	0.89	0.11	−0.04	Tl (mg/kg)	0.51	0.08	0.03	0.54	0.17
V (mg/kg)	−0.50	0.35	0.63	−0.02	−0.12	Mo (mg/kg)	0.25	−0.11	−0.10	− 0.43	0.04
Hf (mg/kg)	0.16	−0.03	−0.15	− 0.93	−0.11	Sr (mg/kg)	0.15	0.08	0.29	0.27	0.81
Zr (mg/kg)	−0.57	0.06	0.03	− 0.79	0.04	CaO (%)	−0.24	−0.31	0.40	−0.01	0.69
Mo (mg/kg)	−0.32	−0.03	−0.14	0.08	0.87	Zr (mg/kg)	0.28	−0.25	0.09	−0.37	0.58
As (mg/kg)	0.44	0.02	−0.42	0.17	0.44	Cr (mg/kg)	−0.50	−0.04	0.46	−0.22	− 0.55
Variance (%)	52.5	16.1	9.4	6.0	3.7	Variance (%)	36.7	15.9	12.8	6.9	4.2
Cumulative Variance (%)	52.5	68.6	78.0	84.0	87.7	Cumulative Variance (%)	36.7	52.5	65.3	72.2	76.4

Bold numbers denote the highest absolute values among the corresponding principal components.

During the LGM, the cold climate resulted in weakened chemical weathering, which can be inferred from the lower CIA values; however, the increased rainfall brought about massive chemical weathering products, which is indicated by the persistently higher K₂O/TiO₂ ratios during this period (Fig. 6). Since the LGM, the warm and humid climate conditions corresponded to higher K₂O/TiO₂ ratios and lower CIA values in the core sediments, indicative of K enrichment in marine sediments and weakened chemical weathering. During the Holocene, the strong southwest summer monsoon prevailed in the BoB, bringing abundant rainfall and intense chemical weathering over the Himalayas and Indian Peninsula (Joussain et al., 2017). The amount of rainfall remained high during the early and middle Holocene but then decreased gradually, while the rainfall simultaneously changed with the K₂O/TiO₂ ratio (Fig. 6). This phenomenon could be linked with the interception of direct access from the G-B drainage to the canyon mouth of the Active Channel when the sea level rose to a certain height at that time.

During the LGM, though the precipitation was higher, the chemical weathering experienced a weakening trend as a result of the cold climate and resulted in a low sea level (Fig. 6). During the Holocene, the climate gradually warmed, and the summer southwestern monsoon intensified (Colin et al., 1999; Kudrass et al., 2001). The elemental ratios of K₂O/TiO₂ descended significantly, while the CIA values ascended notably, indicating the reinforcement of the chemical

weathering during this period, which was consistent with the relative sea level rise and increasing rainfall. To summarize, it is evident that the climate variations played a key role during the chemical weathering process.

4.3. Dynamics of sediment transport

After entering the marine environment, sediments from the northern Himalayas were dominantly transported via the G-B River system to the study area through channels that were widely developed in the submarine fan-Bengal Fan (including the Active Channel). Simultaneously, sediments from the Indian Peninsula were mainly discharged into the BoB by the G-K and Mahanadi Rivers. Previous studies confirmed that fluvial sediments were trapped in the delta and adjacent shelf and the canyon intercepted the sediments, further moving the sediments along the continental shelf (Colin et al., 2006; Curray et al., 2002; Weber et al., 2003). Rapid deposition occurred in the submarine canyon because the abundant discharge of the confluent Ganges and Brahmaputra Rivers entered the canyon head during lower sea level conditions, when slumping occurred in the canyon heads or on the continental slope and generated large turbidity currents (Curray et al., 2002; Suresh and Bagati, 1997). During the LGM, the large turbidity currents reached as far as the distal Bengal Fan, but the amounts of fluvial sediments from the G-B Rivers decreased rapidly during the

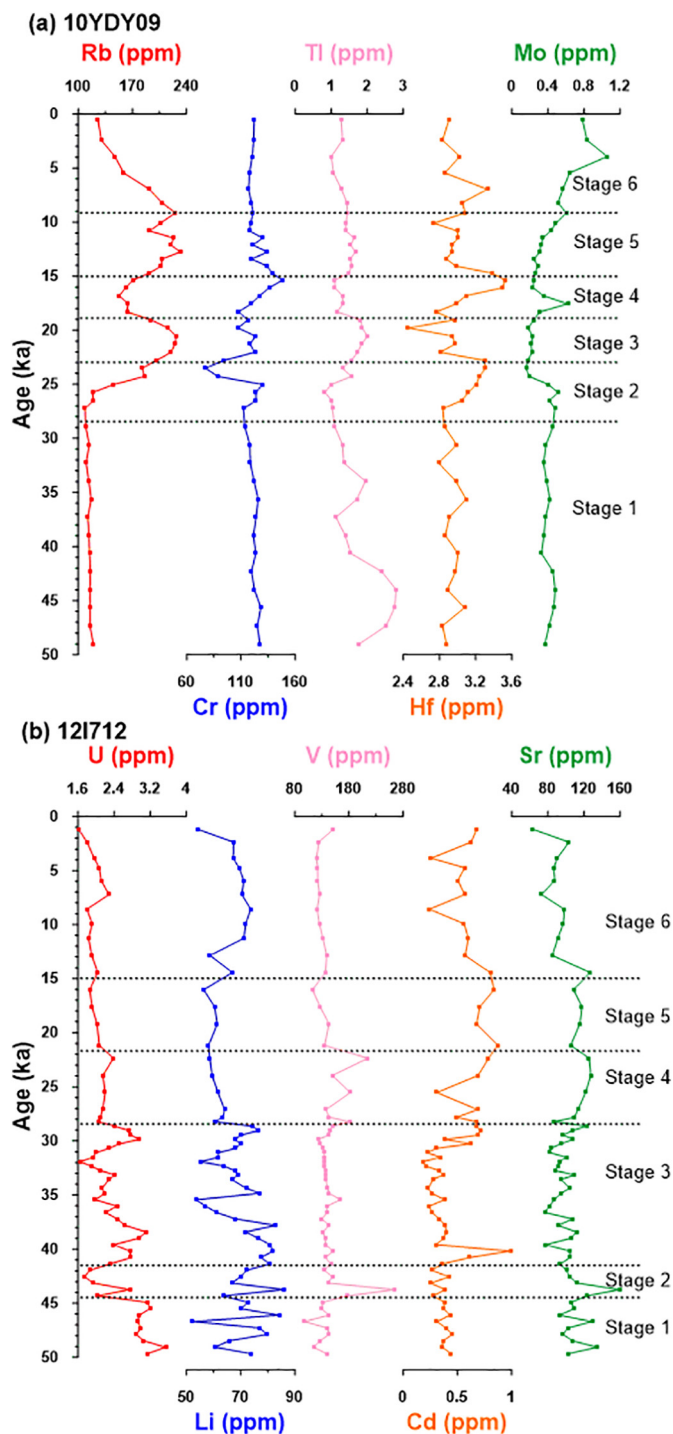


Fig. 4. Variations in the typical trace elements among five principal components in the sediments of cores 10YDY09 (a) and 12I712 (b). The horizontal dashed lines mark the boundaries of the divided stages.

late period of the LGM, according to the provenance analysis of the sediments in core 12I712. During the Holocene, the sea level increased in combination with the warming climate, resulting in the intercepted direct access of the G-B discharge into the canyon of the Active Channel (Curry et al., 2002).

Because there were no channels directly connecting the estuary of the G-K Rivers to the study cores, we considered the transport dynamics of the G-K drainages discharges to be mainly correlated with the EICC. During the LGM, the current circulation in the BoB was dominated by the winter monsoon, and the intensity of the south-west monsoon was

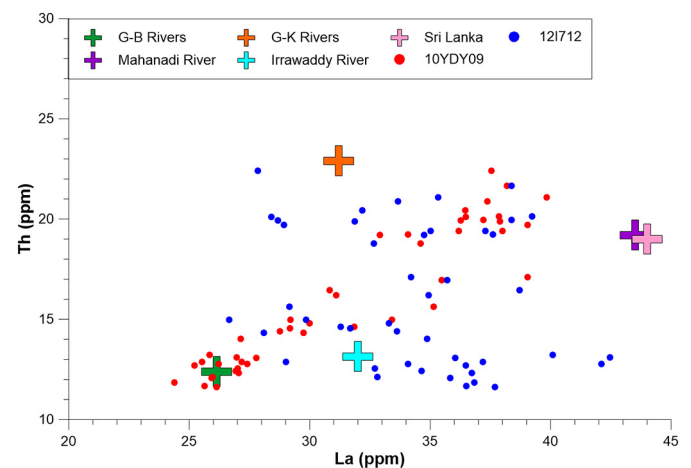


Fig. 5. Discrimination plot of the Th and La concentrations in the sediments of the two cores in the northeastern Indian Ocean and comparisons with the G-B Rivers (yellow shade) (Stummeyer et al., 2002), G-K Rivers (Mazumdar et al., 2015), Mahanadi River (Mazumdar et al., 2015), Irrawaddy River (Garzanti et al., 2016) and Sri Lanka (Prame and Pohl, 1994). Here, we just show the average values of the surface sediment samples (instead of the whole core sediments) for all surrounding possible sources to better compare with the compositions of the various possible sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relatively lower (Li et al., 2018; Sarkar et al., 1990). An investigation of the sediments in the upper Bengal Fan indicated that the Indian summer monsoon was weakened, whereas the winter northeastern monsoon was intensified during that period (Colin et al., 1999; Lupker et al., 2013) because the strong winter monsoon may be caused by the accumulation of glacial ice over the Himalayas and Tibetan Plateau, resulting in a strengthened land-to-sea temperature contrast in the winter (Sarkar et al., 1990). Recent modeling experiments confirm that the Indian materials from the G-K River discharges can be transported via the EICC (Jana et al., 2018). Hence, the sediments from the Mahanadi River may be transported under the influence of channels as well as ocean currents.

5. Conclusions

The major and trace elements in the sediments of cores 10YDY09 and 12I712 along the Active Channel in the northeastern Indian Ocean have been studied. The data allow for a systematic provenance analysis of the core sediments in the Bengal Fan. The REE distribution patterns show the close correlation of the sediment supplement from northern Himalayan material as well as the western Indian Peninsula.

Variations in the elemental ratios of the sediments in cores 10YDY09 and 12I712 reflect chemical weathering in the surrounding sources, which were correlated with the sea level fluctuation and rainfall changes over the past 50 ka. During the LGM, especially the late stage, the chemical weathering in the core sediments was greatly weakened, which is simultaneous with an increase in the fluvial sediments and K enrichment in the study area. In the northeastern Indian Ocean, the global sea level ascended continuously from 120 m below the present level to near the present height, and K enrichment and chemical weathering did not occur. Thus, combined with the rainfall changes, the fluvial sediment did not easily enter the deep-water environments through the channels when the sea level increased to a certain height.

Terrigenous materials from the G-B drainage discharges accumulated during the LGM, which was linked with the strengthened turbidity activity as well as the higher precipitation during that time. During the Holocene, the rising sea level intercepted the direct movement of

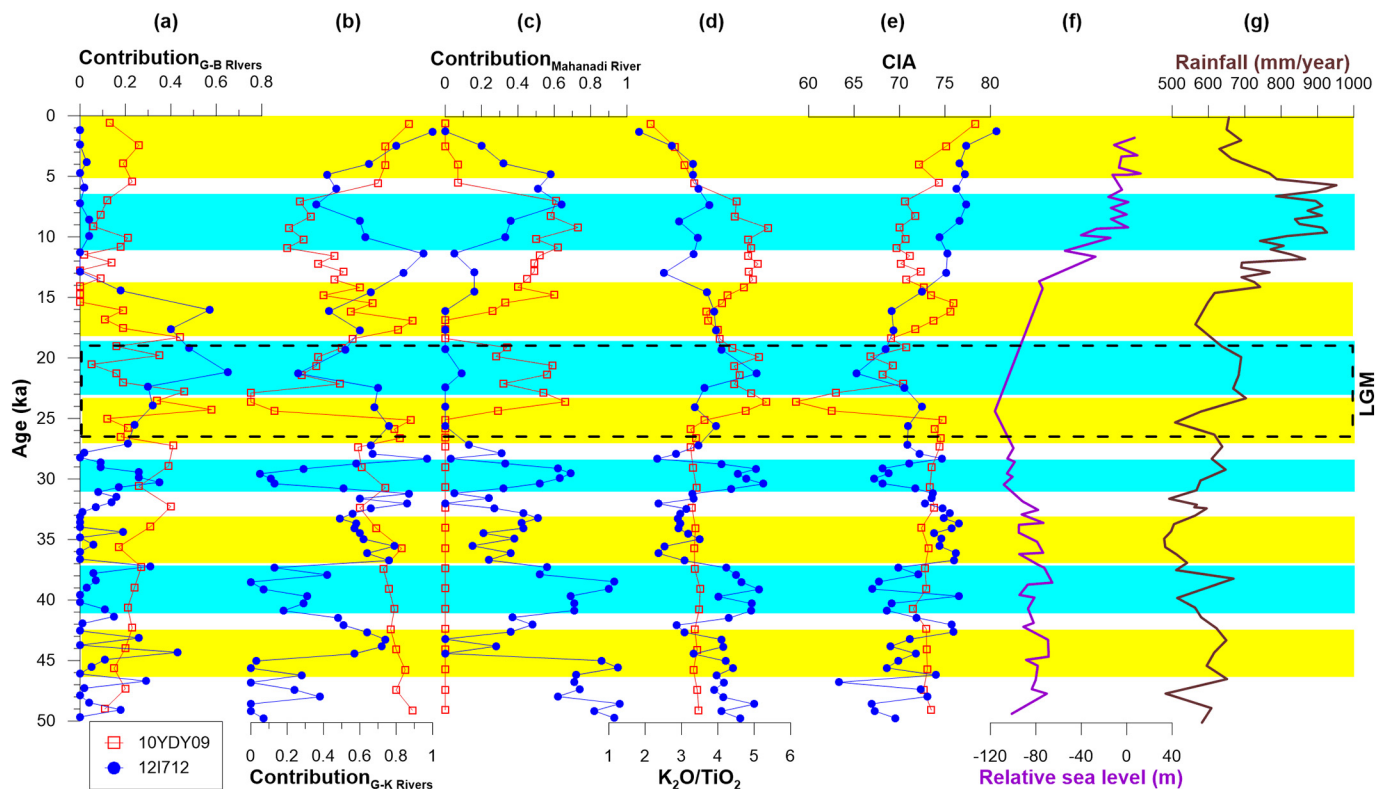


Fig. 6. (a–c) The estimated contributions of the G-B, G-K and Mahanadi Rivers based on the Th and La concentrations, (d) K_2O/TiO_2 and (e) CIA values in the sediments of cores 10YDY09 (red) and 12I712 (blue), (f) global relative sea level (redrawn from (Liu et al., 2017)) and (g) rainfall in the East Asian monsoon area (Beck et al., 2018). LGM denotes last glacial maximum, and yellow and blue shades represent low and high rainfalls, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

terrigenous sediments to the canyon of the Active Channel, resulting in less sediment supply from the G-B Rivers to the area of core 12I712.

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